12 Laser Dynamics

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A main part of our research activities, besides the laser related projects described in the section on surface physics, is the investigation of nonlinear spatio-temporal effects caused by the interaction of resonant laser beams with sodium atoms in the gas phase. A circularly polarized laser beam propagating through sodium vapor can optically pump sodium atoms into a nonabsorbing ground state (optical pumping). This strongly nonlinear mechanism which occurs even at very low light intensities causes an intensity dependent refractive index gradient along as well as transverse to the laser beam propagation direction which may give rise to a number of nonlinear spatio-temporal intensity and polarization pattern creating processes.

Probably the first observations of optical pumping of sodium atoms as beeing the cause for laser beam shape modifications were self-focusing, self-defocusing and self-trapping of the beams [1]. Since then a large number of optical pumping related effects have been observed by various research groups. A collection of effects which we have observed in experiments and described by appropriate models [2, 3, 4, 5] are displayed in fig.12.1.

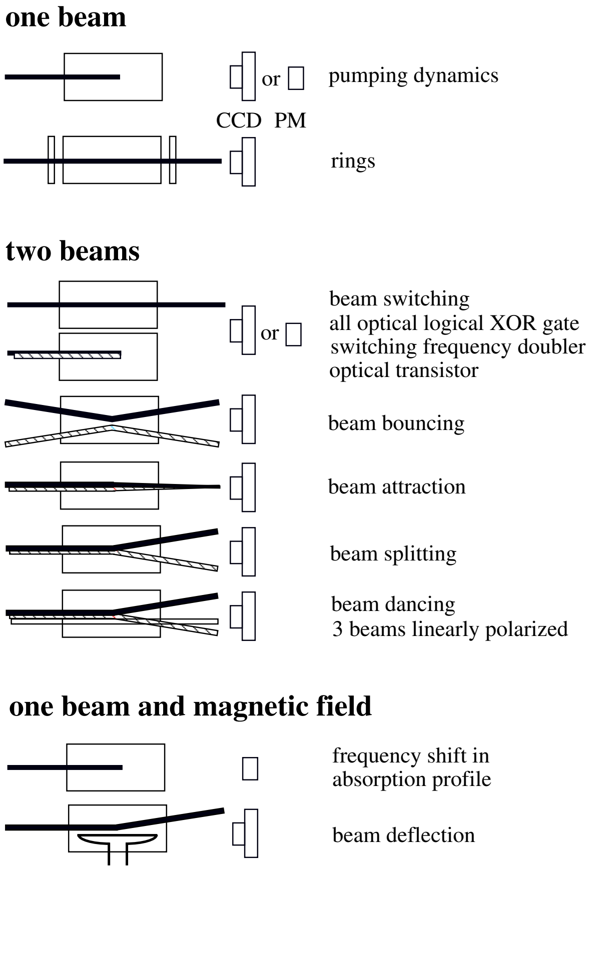

Figure 12.1: Collection of observed effects when circularly polarized laser beams propagate through sodium vapor. CCD: recording by a CCD camera, PM: recording by a photo multiplier.

One of the most basic cases of dynamic behavior, where only a single circularly polarized beam “pumps” its way through the medium, is an important test case for the theory [6] since it demonstrates disagreement by about an order of magnitude between the time scale of optical pumping observed in experiments [7, 6] and predicted by the commonly used $J = \frac{1}{2}$ model. It needed our recently developed model [3], which includes the hyperfine structure of the atomic transition, to obtain the realistic (slower) time scale.

The observed ring patterns [8] caused by a single near circularly polarized laser beam represent a novel phenomenon which combines two processes. The first one is induced gyrotropy in the case of a near-resonant atomic vapor. The second process is that of spatial separation of polarization components which made its first appearance in the form of filaments with opposite circular polarization in sodium vapor [9], but has more recently been observed to occur in a *cylindrically symmetric* manner when an elliptically-polarized beam propagates through a collisionally-broadened $J = \frac{1}{2}$ system.

The effect of beam splitting [10] represents a polarization instability, where an initially "pseudo-linearly" polarized beam breaks up into two circularly polarized beams. Polarization instabilities play an important role e.g. in sodium vapor related work with regard to optical bistability and multistability, polarization switching, self oscillations or chaotic behavior.

Beam bouncing, beam splitting and the mutual attraction of two laser beams shine new light on the related classic experiments of Tam and Happer [9]. In their experients, Tam and Happer observed two major effects. One is the mutual repulsion of two equally circularly polarized beams or the mutual attraction of two opposite circularly polarized beams (beam bouncing or beam attraction) and the other one is the spontaneous break-up of a linearly polarized beam into two distinct beams of opposite circular polarization (beam splitting). Their explanation of the observed effects by introducing gradient forces or ponderomotive forces however is inconsistent [11]. Tam and Happer base their semiclassical and semi-quantitative theory on the belief that the force is transmitted between the beams by sodium atoms in much the same way that virtual photons are believed to transmit the force between the charged particles. Their explanation of the bending of the laser beams is based on the assumption that a sodium atom with "spin up" is repelled by a σ^+ and an atom with "spin down" by a σ^- circularly polarized beam. As a result, the beams bend under the force of reaction. However, in a vapor the atoms fly in all possible directions. The net reaction force therefore vanishes and no beam bending takes place. Furthermore, even if the atoms prefer a flight path between the beams, attraction between two σ^+ beams can not be explaned because the above mentioned reaction force is allways repulsive. An alternative theory [11] assumes an interaction between photons which is mediated by an axial photon [12] (axial vector torsion) leading to a long range spin-spin interaction enhanced by the optically pumped and therefore spin polarized sodium vapor. Fitting the theory to the experimentally determined beam separations of [9] as a function of sodium density, Naik et al. found a coupling strength of the new spin-spin interaction which is about 10^{-9} times smaller than that of the usual electromagnetic spin-spin interaction. This is less than the weak interaction. Its contribution to QED phenoena in vacum is negligeably small but may manifest itself in astrophysical processes through the possibility of photon- neutrino interaction. The force would be Coulomb like and would allow for a photon photon scattering in second order of the coupling strength rather than in fourth order as is the case in usual QED photon-photon scattering. This theory, however, which would have implications related to the debate about a spin dependent fifth force, the stability of the electron or to the existence of an analogous Aharonov-Bohm Effect for photons and contributions to the hyper fine level splitting, has been questioned by Oblukhov et.al. [13]. Until today this interesting subject has not been fully understood. Unfortunately the second observation of Tam and Happer, the beam splitting, has not been adressed by these autors at all. Considering our own results in connection with beam bouncing in the presence of buffergas, which enhances optical pumping, reduces atomic diffusion and allows for models explaining all observed behavior, we favour a more simple explanation in terms of refractive index gradients which attract or repell the beams depending on their circular polarization.

The occurence of beam splitting is most likely due to optical pumping effects combined with fluctuations of the atomic density, the laser beam intensity, the polarization, small residual magnetic fields and deviations of the beam intensity distribution from an ideal Gauss profile. These imperfections break the cylindrical symmetry and can initiate beam splitting of a linearly polarized beam. The full theoretical treatment would involve Doppler broadening and nonlocal polarization effects due to atomic motion between the laser beams which is not yet included in our present models.

Involving magnetic fields is of particular interest since they affect the optical pumping induced alignment of the atomic magnetic moments. A most striking example is the large apparent shift of absorption profiles [14] in the case of a single circularly polarized laser beam propagating through sodium. The effect is caused by the combination of three well known effects "optical pumping", "light-shift" and "Larmor precession".

A further astonishing effect (described in more detail in the following subsection) due to the combination of optical pumping and magnetic fields is the deflection of a laser beam by the inhomogeneous magnetic field of a current carrying wire.

While the steady state behavior of these effects has been observed and described in the past, only recently the modeling of the dynamics of the pattern formation processes has become possible by considering all hyperfine states of the atomic D_1 transition.

Beam deflection by a current carrying wire

A circularly polarized laser beam propagating through sodium vapor is deflected [15] by the inhomogeneous magnetic field from a nearby electric current-carrying thin wire aligned parallel to the beam (fig.12.2).
The effect arises from the refractive index gradient induced by magnetic-field-modified optical pumping. The time of order 100 ns needed for the beam to switch between undeflected and deflected positions is determined by the average Larmor precession period and is two orders of magnitude shorter than the optical pumping time. The electric current of 60 mA needed to produce an appreciable steady-state beam deflection—28 μm measured at the cell output window as shown in Fig. 12.2 —gives rise to a slight temperature change in the wire. After about 5 ms the heating effect causes the local sodium density to rise and leads to an increase of beam deflection. "Steady-state" deflections, shown in Fig. 12.2(right), are recorded between 1–30 μs after current initiation; sufficiently delayed to avoid the initial transients in beam displacement but before the onset of thermal effects.

The basic mechanism can be understood by considering the effect in terms of an encoding/diffraction sequence. A somewhat over-simplified view (which ignores the spatial variation of intensity across the beam as well as absorptive effects) is that the optically-pumped medium can be approximately described as a glass prism of refractive index less than unity. The 'thick' edge of the prism is adjacent to the wire where the high magnetic field inhibits optical pumping, and the medium has near-normal refractive index. Further from the wire, where the magnetic field is insufficiently large to suppress optical pumping, the medium is bleached with a refractive index tending towards free space; here, the prism has its 'thin' edge. The net effect of the prism is to phase encode the laser beam and bend the propagation direction away fom the wire.

An important issue is that the steady-state density distribution of absorbing atoms can change much faster by the application of a transverse magnetic field gradient than by optical

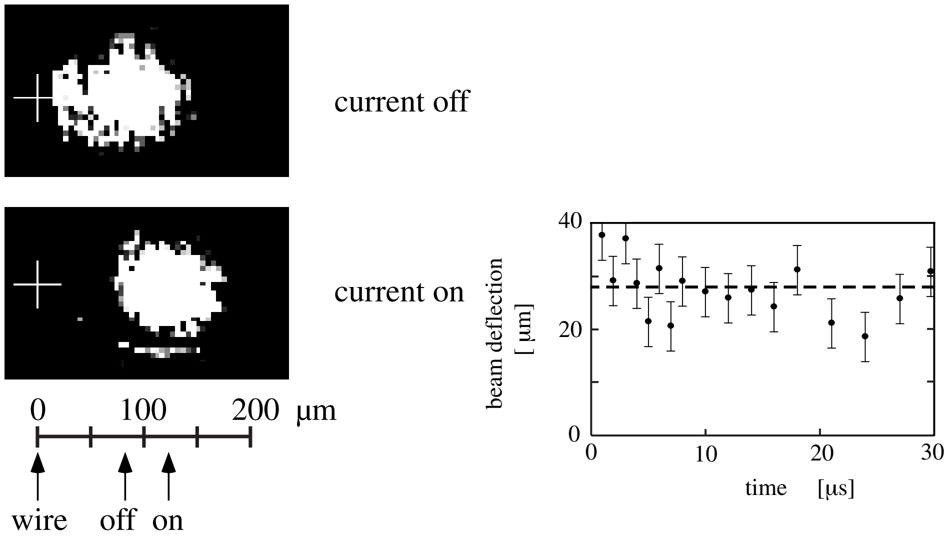

Figure 12.2: Left: Undeflected and deflected beam spots at the output window of the sodium vapor cell before and after the electric current through the wire has been switched on. For the determination of the beam positions only pixels brighter than 50% of maximum are considered. Right: Beam deflection during the first 30 μs after the current has been switched on. Error bars indicate the standard deviation of 10 measurements taken within 3 minutes. The main causes for the scatter of single measurements are the fluctuation of the input laser intensity as well as density fluctuations inside the vapor cell. The dashed line marks the mean deflection of (28±2) μm averaged over the displayed series of 17 times 10 measurements.

pumping.

In Fig. 12.3 we present simulation results showing how the spatial distribution of the field intensity evolves.
When there is no electric current, the beam establishes an undeflected steady-state profile after about 20 μs (Fig. 12.3(a)). Upon application of the current at $t = 0$ the beam quickly deflects to its final position: Fig. 12.3(b) gives the situation after 50 ns. The reason for this rapid response is that the magnetic field depolarizes the ground state within a fraction of an average Larmor period (i.e. sub-microsecond). Although the deflection suffers little further change the output intensity at beam center continues to grow as optical pumping becomes more complete, and eventually a steady state is achieved, as shown in Fig.12.3(c), 20μs after the current is turned on. The simulated beam deflection in the final steady-state, 34μm, is in good agreement with experiments shown in Fig.12.2, given that all parameters used in the theory correspond to experimentally determined values without fitting. The destruction rate Γ_l of the ground-state orientation includes the effects of radiation trapping and is determined as described in [14].

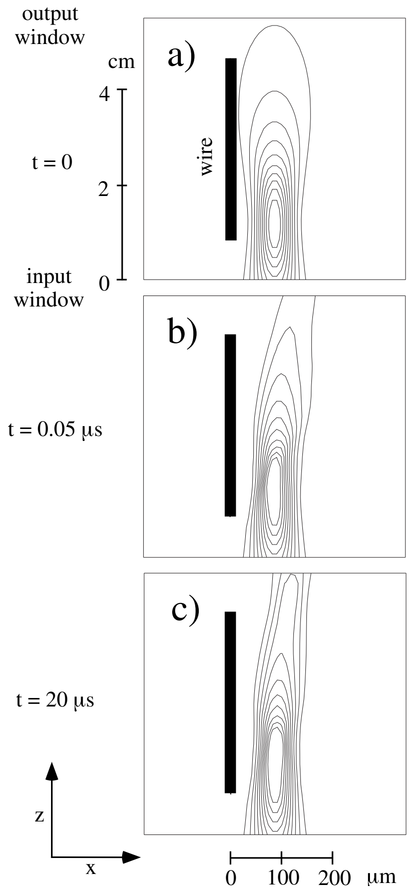

Figure 12.3: Intensity contour plots of the laser beam in the $y = 0$ plane from the simulation: (a) steady-state with no current; (b) 50 ns after the current is turned on; (c) steady-state 20 μs after current is turned on. The wire is parallel to the z axis at $x = 90$ μm, $y = 0$. From 6 mW input-beam power, 5.5 mW penetrates the vapor in (a) and 1.8 mW in (c).

References

[1] J.E. Bjorkholm and A. Ashkin. Cw self-focusing and self-trapping of light in sodium vapor. *Phys. Rev. Lett.*, 32:129–132, 1974.

[2] R. Holzner and S. Dangel. Optical pumping-induced spatio-temporal modifications to propagation, polarization and intensity of laser beams in sodium vapour. *J. Europ. Opt. Soc. B*, 10:R1–R22, 1998.

[3] S. Dangel and R. Holzner. Semi-classical theory for the interaction dynamics of laser light and sodium atoms including the hyperfine structure. *Phys. Rev. A*, 56:3937–3949, 1997.

[4] S. Dangel and R. Holzner. Dynamics of light pattern formation for polarized laser beams propagating through sodium vapor. *J. Opt. Soc. Am. B*, 15:594–606, 1998.

[5] R. Holzner, J. Simonet, L. Flepp, B. Röhricht, P. Eschle, S. Dangel, U. Rusch, H. Schmid, and E. Brun. Using nuclear spins, radio waves, sodium atoms, and laser light to investigate spatiotemporal nonlinear systems. *Optical Engineering*, 34:2315–2323, 1995.

[6] S. Dangel, P. Eschle, B. Röhricht, U. Rusch, H. Schmid, and R. Holzner. Dynamics of laser beam switching in sodium vapor. *J. Opt. Soc. Am. B*, 12(4):681–686, 1995.

[7] D. Suter. Optically excited Zeeman coherences in atomic ground states: nuclear-spin effects. *Phys. Rev. A*, 46(1):344–350, 1992.

[8] B. Röhricht, U. Rusch, S. Dangel, H. Schmid, P. Eschle, R. Holzner, and W.J. Sandle. Optical pumping induced ring structures of polarized laser light propagating through sodium vapor. *J. Opt. Soc. Am. B*, 12(8):1411–1415, 1995.

[9] A. C. Tam and W. Happer. Long-range interactions between cw self-focused laser beams in atomic vapour. *Phys. Rev. Lett.*, 38(6):278–282, 1977.

[10] B. Röhricht, A. W. McCord, M. Brambilla, F. Prati, S. Dangel, P. Eschle, and R. Holzner. Spatial separation of circularly polarized laser beams in sodium vapor. *Opt. Comm.*, 118:601–606, 1995.

[11] P.C. Naik and T. Pradhan. Long-range interaction between spins. *J. Phys. A*, 14:2795–2805, 1981.

[12] T. Pradhan and A. Lihiri. Finite quantum electrodynamics. *Phys. Rev. D*, 10:1872–1882, 1974.

[13] Y.N. Oblukhov and I.V. Yakushin. Experimental restrictions on spin-spin interaction in gauge gravity. *Int. J. Theor. Phys.*, 31:1993–2001, 1992.

[14] B. Röhricht, P. Eschle, C. Wigger, S. Dangel, D. Suter, and R. Holzner. Large frequency shifts of absorption profiles due to the combination of optical pumping, light shift, and magnetic fields in sodium vapor. *Phys. Rev. A*, 50(3):2434–2437, 1994.

[15] R. Holzner, P. Eschle, S. Dangel, R. Richard, H. Schmid, U. Rusch, B. Röhricht, R. J. Ballagh, A. W. McCord, and W. J. Sandle. Observation of magnetic-field-induced laser beam deflection in sodium vapor. *Phys. Rev. Lett.*, 78:3451–3454, 1997.